SOME ASPECTS OF RESEARCH ON NUCLEAR POWER FOR AIRCRAFT

by

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It is a pleasure to speak to you this evening on the general subject of the application of nuclear power for the propulsion of aircraft. This is a subject that I think needs to be discussed and one in which progress in the field has perhaps been slowed by lack of discussion.

Interest in the subject arises from its importance to the future development of high performance aircraft, and can perhaps best be high-lighted if I bring again to your attention results that I presented in the Wright Brothers Lecture of 1948. These results are shown in the first figure (figure 1) on which the flight range of airplanes is plotted against air speed. The curve shown is an envelope of the range performance for optimum combinations of engines and aircraft that are flown at their best speeds and altitudes. At the lower speeds shown on the slide the envelope curve was developed by drawing tangents to the performance curves of aircraft equipped with propellers. Whereas, in the higher air speed range at transonic and supersonic speeds tangents were drawn to the performance curves obtained with jet engines.

These results were obtained by analysis of many engine-airframe combinations and the calculations attending the analysis include many questionable assumptions regarding values of engine weights, aircraft weights, and values of the aerodynamic efficiency. No defense of particular values or assumptions that are included was offered and this questionable nature is indicated by the width of the performance line drawn on the figure. Recent recalculations show that the results presented on the figure in 1948 are still generally valid.

In my original discussion of the results I said the curve does accurately disclose that the ultimate range is sharply reduced as the aircraft speed is increased up through the transonic-speed region, after which the range decreases at a slower rate. Large increases in propulsion-system performance above those assumed in preparing the chart are not too likely for engines burning either conventional petroleum fuels or special fuels. Further increases in range in high-speed flight will, therefore, depend on new aerodynamic developments that will reduce the aircraft skin friction and wave drag or upon the successful development of a nuclear-energy power plant with a sufficiently high value of the weight parameter F/W_e to make it useful for high-speed propulsion.

Despite important increases in aerodynamic efficiencies for aircraft at transonic and supersonic speeds since 1948, nuclear power still remains as the "shining-hope" for increasing the range of aircraft at high speeds and for increasing aircraft ranges to values unobtainable with conventional or special chemical fuels. A long range bomber may carry as much or more than 100,000 pounds of fuel. A piece of U-235 with the same energy content would weigh only 0.05 pounds.

The potentiality of nuclear power for long range at supersonic speeds provides the key for establishing the emphasis to be placed on this problem. To my mind, our security requires that the nuclear power application to the airplane must be expedited with a feeling of real urgency and necessity.

Committee discussions of feasibility have now served their purpose and augmented efforts in the applied sciences and in engineering should take their place. Fortunately, the fundamental reactor sciences are sufficiently well established so that efforts in the applied science and engineering fields can be applied intelligently, and experience shows that the results obtained in applied research and engineering are about proportional to the effort expended. The support of the Atomic Energy Commission and the military services of programs in this area as has been reported in the press is indeed praise-worthy.

Engine Cycles

I will continue by reviewing for you some possible engine cycles. This material has been presented before by Kalitinsky in his note-worthy paper several years ago (reference 1), by Anderton in his excellent review in Aviation Week (reference 2), and by others.

The next figure (figure 2) shows a simple power plant for aircraft nuclear propulsion. It is the turbojet engine with the combustion chamber replaced by the nuclear reactor. The air enters the compressor, passes through the reactor where it is heated by flowing over elements containing uranium; it then passes through a turbine and is discharged rearwardly through a discharge nozzle to provide thrust. The power generated by passage of the air through the turbine drives the compressor through the shaft which joins them. The airplane is, of course, propelled by the high velocity jet which discharges from the exhaust nozzle.

Air is a poor heat transfer medium. Higher power generation can be obtained by using a liquid coolant in the reactor and transferring the heat from this liquid to the air in a heat exchanger. This is illustrated in figure 3. The powerplant is similar to the one shown in the previous figure except that a secondary loop is shown in which a liquid is pumped through the reactor and then through the heat exchanger through which flows the air from the compressor. This heat exchanger can have considerably more heat transfer area than is permissible in the reactor and hence can transfer more heat to the air than can the reactor with direct air cooling. Because the fluid must remain liquid at the high temperatures involved, and because it must have a low capture cross section for neutrons, only a small number of coolants are suitable. These limitations have led to the consideration of such materials as molten sodium, lead bismuth and other unconventional materials as coolants. The determination of the heat transfer data on these materials is one of the current fields of research associated with the development of the nuclear powerplant.

A third type of nuclear powerplant is shown in figure 4. It is a steam turbine system. Water is pumped through a reactor where it picks up heat. It is held at a very high pressure in order not to flash into steam within the reactor. The water than flows into a turbine where the pressure is reduced and it flashes into steam which drives the turbine. The turbine supplies power to the propeller shaft and to the water pump. The steam then passes from the turbine to the condenser and back to the pump. The condenser is cooled by an air blast from the propeller. The air blast from the propeller provides the thrust for the airplane. For stationary power generation, the propeller can be replaced by an electric generator and the condenser can be cooled by water taken from a convenient river.

Since it is of interest to use nuclear propulsion to increase the range performance of aircraft particularly at high speeds and altitudes, results of an elementary cycle analysis will be shown to emphasize the importance of cycle temperature.

Low cycle effectiveness in the nuclear airplane does not reflect itself in aircraft range as is conventional for the hydrocarbon-fueled airplane. If the airplane will fly and land at all, its range will be more than adequate. Rather, the cycle characteristic determines whether or not the airplane will fly and how heavy it will be. Since the airplane weight determines the economics of the entire program, it has been chosen as the variable to express cycle effectiveness. Relative weight is used because it does not reveal weight values, and because it adequately demonstrates the point of interest.

For the analysis, a liquid metal cycle was chosen similar to that shown in figure 3. No reactor assumptions are needed since the changes in relative airplane weight shown are due only to the engine installations exclusive of the reactor and shield. The analysis is,therefore,not conservative and the effect shown will in each case be accentuated if a complete analysis is made.

First is shown (figure 5), the effect of altitude on the relative aircraft weight at a fixed flight speed. The importance of high cycle temperatures is clearly indicated by the approximately 50 percent reduction in relative airplane weight at 50,000 feet altitude resulting from increases in cycle temperature from 1800° R to 2400° R. Further, the attainable altitude is higher at the higher temperature cycles.

The effects of flight Mach number on the relative weight are shown in figure 6 for the 2400° R cycle temperature. Even at this temperature at high altitudes, the relative airplane weight increases with Mach numbers at an undesirably high rate. Higher temperatures than 2400° R will no doubt be desirable.

The most difficult scientific and engineering problems that are encountered in the aircraft nuclear field originate from the high temperatures required in many of the propulsion cycles. Some of the material and heat transfer researches under way at the Lewis Laboratory will be used to illustrate the problem fields.

Materials

Studies of materials for the nuclear propulsion systems have stimulated many interesting and difficult research investigations. Materials with satisfactory physical properties at very high temperatures are required as was revealed in the foregoing discussion of cycle performance. The need for low neutron capture cross sections seriously limits the choice of reactor materials. In screening the materials available for the reactor a further requirement is compatability between the reactor structural material and the coolants so that problems of corrosion and mass transfer are avoided. The ductility of the material is of great concern because sudden changes in temperature usually from rapid insertion of control rods may cause failure from thermal shock in non-ductile materials. The strong susceptibility of some materials to damage or change in properties as a result of nuclear radiation eliminates them from consideration.

High stresses such as are encountered in the rotating turbine blades of gas turbine engines are fortunately not a problem. The researches that have been conducted on high-temperature turbine material, however, have provided a starting point for the investigation of high-temperature reactor materials and have contributed immeasurably in the development of the staff and literature needed in the newer field. Some researches in progress at the Lewis Laboratory on reactor materials will be briefly sketched in the following paragraphs.

As just mentioned, a serious problem encountered with structural materials and coolants for nuclear reactors is the occurrence of corrosion and mass transfer. It occurs to a varying degree with both liquid metals and molten salts. It is characterized by the build-up in the coolant of products of the reaction between the coolant and the containing or structural material together with the deposition of crystals of container metal on the cooler walls of the system. That is, the coolant dissolves material from hot regions of the reactor and deposits the material in cooler regions of the circulating system. Thus, in addition to weakening the structure, mass transfer may cause plugging of important passages. The Lewis Laboratory is carrying out an investigation in order to gain an understanding of the mass transfer phenomenon and to find a combination of coolant and container material for which the effect is small enough to eliminate it as a limiting factor in the life of the reactor.

The experimental program is divided into three parts: (1) studies designed to determine the mechanism of the mass transfer process; (2) studies under static conditions to determine the relative usefulness of systems embodying improvements suggested by the results obtained in (1); and finally (3) by flow tests of the most promising systems. The flow apparatus is shown in figure 7. This apparatus permits independent variation of fluid velocity and temperature gradient.

The corrosion system contains no other metal except that under study and requires no pump, valve or flowmeter. A combination of crankshaft and parallelogram type restraining mechanism results in motion of the specimen mounting plate such that any point on its surface described a circle with radius equal to the crank throw. Under these circumstances, the fluid in the toroidal specimen makes one circuit of the toroid for every revolution of the crankshaft.

Many interesting results have been obtained in the flow apparatus and an important conclusion is that static studies of mass transfer and corrosion may be misleading for studies of dynamic flowing systems.

Another important problem in the operation of nuclear reactors is the damage the radiation produces in matter. Thus, at the very high fluxes of neutrons and fission products resulting when such a reactor is run with a high power output, the fuel elements, structural components, and control equipment can all undergo very serious changes in mechanical (and other) properties. In order to predict such effects and choose and prepare the materials employed, it is important to understand the cause of these changes. In metals, at least, the changes are known to result mainly from collisions between heavy charged particles and the atoms of the metal which dislodge the latter atoms from their normal positions. Such collisions occur with appreciable frequency only when the particles are moving relatively slowly. Therefore, it is important to study the behavior of heavy charged particles with low energies as they slow down.

Radiation damage measurement in reactors, cyclotrons, and other particle accelerators are in progress in many research establishments. Fortunately, the collisions occur in almost the same way in a gas as in a metal, since even for slow charged particles the binding between the atoms of the metal is small compared to the energy of the particle. Therefore, it is possible to obtain the information needed to understand collisions in a solid by carrying out an investigation of collisions occurring in a gas. The use of the gas has some advantages because it increases manyfold the short path length of the charged particles especially if the lightest gas, namely hydrogen, is used at reduced pressures. Furthermore, processes occurring in a gas can be studied with the aid of a cloud chamber in which the paths of individual particles are made visible so that collisions may be observed directly. It is necessary in carrying out such investigations to use particles of known energy. We have slowed down particles from a natural radioactive emitter and selected those of the desired energy with a magnetic analyzer which admits them through a thin nylon foil to the chamber. The picture (figure 8), shows the chamber with the analyzer and associated equipment.

We have been carrying out studies of the tracks of low energy alpha particles (charged helium atoms) in this cloud chamber. In this work we have been measuring the lengths of the tracks and the extent to which they deviate from straight lines. The length, of course, is an indication of the rate at which the particles lose energy. By analyzing the distributions of the lengths of tracks of particles of a given energy, we can obtain an estimate of the amount of the energy that is lost in collisions of the type leading to radiation damage. The deviation of the tracks from a straight line is a fairly direct measure of the extent to which the collisions of interest occur because the alpha particles in losing energy through such collisions are much more deflected than when losing energies in other fashions. The results show that these collisions are indeed very frequent at low energies. In addition, all these results are of importance in nuclear physics generally.

Thermodynamic data enable one to predict the behavior and usefulness of materials at high temperatures. Refractory materials such as intermetallics which look promising for use under conditions of high temperature and radiation flux to be encountered in power reactors are relatively new, and thermodynamic data for them are almost completely lacking. The figure 9 illustrates an apparatus used for the determination of vapor pressures at high temperature. From the vapor pressure variation with temperature, can be computed several of the thermodynamic constants of interest.

The vapor pressure determination involves the measurement of the rate of loss of weight of a specimen. The specimen is induction heated with a device which permits close control of temperature.

Another area in which vapor pressure studies are useful is in study of the types of chemical binding in alloys. This is an important problem in the development of intermetallic compounds and cermets for high temperature turbine blades.

Heat Transfer

A principal limitation on the power level of a reactor is the amount of heat which can be removed from it. Among the best mediums for withdrawing heat from a reactor are liquid metals. This is because liquid metals have high thermal conductivities, are liquid over wide ranges of temperature, and are not subject to decomposition under radiation. Because of their high thermal conductivities, however, the convective heat transfer characteristics of liquid metals are not predictable from the familiar relationships which apply to gases and to liquids of lower conductivity. Certain theoretical relationships were proposed for liquid metal heat transfer but, at the time, the experimental evidence was meager and contradictory.

As a consequence of the above considerations, the NACA Lewis Laboratory has constructed and operated an experimental apparatus for the determination of the heat transfer characteristics of lead-bismuth eutectic. Lead-bismuth eutectic is a liquid metal of interest because of its low melting point, low absorption cross section for thermal neutrons, and non-flammability. A picture of the lead-bismuth heat transfer rig is shown in figure 10. Lead-bismuth flows from the storage tank (A) to the pump (B) and is then pumped through the test and heating section (E and F), a water cooler (G), a regulating valve (H), a flow-measuring tank (I), and back into the storage tank. Also seen in the picture are the pump motor (C) and variable speed drive (D), the transformer (K) which supplies electric power to heat the lead-bismuth, and the thermocouple-cold-junction box (J).

The test and heating section consists essentially of one stainless steel tube suspended within another. The section is mounted vertically and liquid metal flows upward in the inner tube and downward in the annular passage between the inner and outer tubes. The upper portion (F) of the section is heated by passing an electric current through it. Therefore, in the lower portion (E), which is the test section proper, the liquid metal is at a higher temperature in the annulus than in the center tube, and heat is transferred from the liquid metal in the annulus to that in the center tube. Mixing chambers were provided at each end of the test section for both the inner and outer passages for the measurement of bulk temperatures.

The results of the investigation indicated that heat transfer coefficients for lead-bismuth eutectic were 60 to 70 percent of the values predicted by the theoretical relationships proposed for liquid metals. Experiments of earlier and later investigators, using lead-bismuth eutectic, sodium-potassium mixtures, and mercury, give heat transfer coefficients ranging from 20 to 100 percent of the values predicted by the proposed theoretical relationship. The spread in experimental data is unexplained at present and the precise values of liquid metal heat transfer coefficients are still in doubt.

The good moderating properties of water and the possibility of freedom from corrosion invite the consideration of water as a reactor cooling medium. The temperatures encountered in a nuclear reactor, however, require the water to be under high pressure where very little heat transfer information is available.

Shown in figure 11 is a photograph of the apparatus used to measure heat transfer coefficients from metal to high pressure water. The apparatus is a closed loop consisting of an electrically heated test section, a heat exchanger to remove the heat, a circulating pump, and flow meters to measure the flow. The system is designed for pressures up to 5000 psi and temperatures up to 1000° F. The system is pressurized mainly by the expansion of the water when the loop is brought up to temperature.

The test section used is shown in the next photograph (figure 12). An inconel tube 25 inches long with an inside diameter of 1/2 inch is electrically insulated from the rest of the loop. Heat is generated in the tube walls by an alternating current controlled by a saturable reactor. The electrical heating equipment is designed for 100 KW at 25 volts and 4000 amperes. Tube wall temperatures are measured with chromel-alumel thermocouples spot-welded to the outer surface of the tube. The same equipment is intended to furnish data under boiling conditions.

Because of the potential usefulness of molten salts as a high-temperature heat transfer media, molten sodium hydroxide heat transfer characteristics were investigated in apparatus shown in the next figure (13). Heating data were obtained in a 1/4 inch electrically heated inconel tube for a range of Reynolds number from 5300 to 29,000, corresponding to velocities from 3.8 to 15.4 feet per second, average surface temperatures from 730° to 970°F, average fluid temperatures from 710° to 920°F, and heat-flux densities up to 226,000 Btu per hour per square foot.

Cooling data were taken concurrently with the heating data, with sodium hydroxide flowing through the center passage of a single-tube, inconel, counter-flow, sodium hydroxide-to-air heat exchanger. Data were obtained for a range of Reynolds number from 6500 to 30,000, corresponding to velocities from 5.9 to 15.4 feet per second, average surface temperatures from 710 to 915°F, average fluid temperatures from 725° to 940°F, and heat-flux densities up to 120,000 Btu per hour per square foot.

The figure shows an over-all view of the test setup. Sodium hydroxide is circulated by a submerged centrifugal pump, through the heating test section, cooling test section, heat exchanger, and volume measuring tank. From the volume measuring tank the molten sodium hydroxide returns to the sump tank. The heat exchanger was used to maintain a constant inlet temperature to the heating test section, since at a high rate of heat input to the heating test section, the cooling test section was inadequate to remove this heat. The volume measuring tank was used to calculate the weight-flow rate of the molten sodium hydroxide.

In nuclear powered aircraft cycles, heat exchangers must possess the following characteristics: small volume flight weight, high heat transfer per unit volume, low air pressure drop, high operating temperature, and several other characteristics not found in currently available heat exchangers. In view of this, the Lewis Laboratory has constructed a facility for evaluating the performance of liquid metal to air heat exchangers (figure 14).

In this facility, liquid sodium is electrically heated to approximately 1500°F and circulated through the heat exchanger by means of a variable speed centrifugal pump. The facility is designed to have an input power of 500 kilowatts, a sodium flow rate of 50 GPM, and air flow rate of four pounds per second.

Types of heat exchangers currently under consideration are: (a) shell and tube with the liquid metal as the shell fluid; and (b) finned tube with the liquid metal as the tube fluid. Both of these heat exchangers are of the counter-flow type.

For comparison of heat-transfer performance for various working fluids a plot was made (figure 15) of Nusselt number times thermal conductivity, $\left(\frac{hD}{K}\right)$ K, Reynolds number, $\left(\frac{GD}{\mu}\right)$. The McAdams equation, $Nu = 0.23\ (Re)^{0.8}\ Pr^{0.4}$, was used to determine the heat-transfer coefficient for air, helium, water, and sodium hydroxide. Heat-transfer coefficients for lithium, sodium and lead-bismuth were determined from the equation derived by R.N. Lyon, $Nu = 7.0 + 0.25\ (Re)^{.8}\ (Pr)^{.8}$. The properties for all media except sodium hydroxide were taken at 400° F, the latter was taken at 700° F.

Liquid metals offer an advantage over the other heat-transfer media when high heat-transfer coefficients are required and when high temperature must be used. They bring with these advantages the problem of possible greater expense and the problem of unique handling.

The gases in general cannot compete with liquid metals from the standpoint of heat-transfer coefficient, and neither can organic compounds without a change of phase (boiling or condensing). The latter are limited in their temperature range by chemical decomposition. The principal competitor with liquid metals from the standpoint of high heat-transfer coefficient is water, however, its application is limited by high pressure.

No rigid rule can be made to determine which media is preferred for a particular system, but a complete analysis of the system, taking into account all of the physical properties of each heat transfer media, is required before a choice can be made.

Concluding Remarks

In this brief and sketchy outline of a few of the problems of nuclear propulsion systems, I have failed to mention the reactor shield which more than any other component of the system determines the aircraft weight. Another important omission is in the field of reactor analysis where much original and development work yet remains to be accomplished. These and other important omissions were necessary to limit the time of presentation.

Many organizations are cooperating to obtain the vital information needed for the aircraft nuclear powerplant. I believe the problems should be attacked with a feeling of urgency. All who participate are pioneers in initiating the Atomic Power Age and we are fortunate to be able to take a part.

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